CHAPTER 9

Air Pollution: Role in Climate Change and Its Impact on Crop Plants

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9.1 INTRODUCTION

Global warming relating to climate change has been one of the most debated topics of the 21st century. A report by the Intergovernmental Panel on Climate Change (IPCC, 2014) has strongly highlighted the dominance of anthropogenic influences in inducing extensive changes in climatic systems and the concomitant rise in average temperature along with changed precipitation patterns globally. As per the assessment details provided by the IPCC (2014), each successive decade since 1850 has been experiencing higher temperatures in comparison to the preceding decades. Global agricultural production is facing challenges due to such fluctuations in climatic variability (Oseni and Masarirambi, 2011), which are increasing

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at an alarming rate. According to estimations, Asseng et al. (2015) reported a 6% decline in global wheat production for each 1°C of further temperature increase which predicts a direct risk to global food security. Therefore, world food production is currently facing the risk of unprecedented shifts in the spatial and temporal patterns of climatic variables, such as the rising of sea levels, prevalence of much higher temperature than previously, higher incidences of extreme weather events, enhancement of atmospheric CO_2 concentrations, and unpredictable rainfall patterns (Chen et al., 2015).

Scientific evidences have displayed that many anthropogenic activities have significantly contributed to the surface temperature increment since 1951. Global concentrations of atmospheric CO_2 have enhanced since the preindustrial era from 280 ppm (IPCC, 2014) to the present level of 410 ppm (www.esrl.noaa.gov/gmd/ccgg/trends/) and is further predicted to increase to 448 ppm by 2050 (IPCC, 2014). Such a substantial rise of global atmospheric CO_2 concentrations and alterations in rainfall distribution patterns are expected to have far reaching consequences on crop growth and production, thereby threatening global food security in future. Of late, this subject has received stupendous attention with an enormous amount of research being conducted in order to better understand crop responses to changes in climatic variability. With growing concern for agriculture and alterations in the Earth's system dynamics, the direct and indirect impacts of climate change have been critically analyzed here along with the need for plausible mitigation strategies that can be adapted by farmers through different agronomic practices to cope with the threat of food insecurity.

9.2 FACTORS DRIVING CLIMATE CHANGE

The Earth's climatic system is of a dynamic nature and is inherently subject to continuous processes of change since preindustrial times, mainly associated with anthropogenic activities and to a lesser extent to sources of natural origin. Humanity's understanding of the global climate system has been challenged by the complex interconnected nature of its different components, such as atmosphere, biosphere, cryosphere, and hydrosphere. However, the major physical drivers of climate change are initially associated with atmospheric composition, the cloud effect, and radiative forcing. The drivers of climate change can be categorized into those of natural or those of anthropogenic origin (Fig. 9.1).

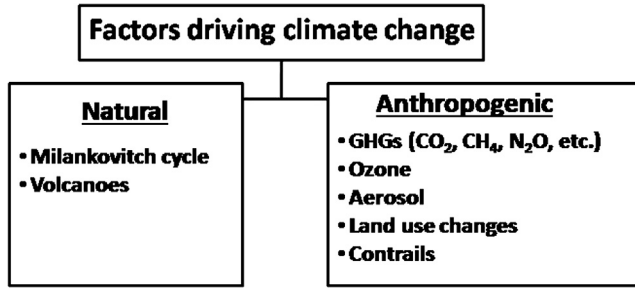

Figure 9.1 Various natural and anthropogenic factors influencing climate change.

9.2.1 Natural Drivers

9.2.1.1 Milankovitch Cycle or Changes in the Earth's Orbit

The emerging consensus regarding the rise of global mean temperature has been a topic of discussion lately and researchers mostly believe that anthropogenic emissions are a major cause driving such changes. However, such variation in the Earth's mean temperature can also be associated with both long-term and short-term natural cycles occurring over considerable time periods. Such natural cycles are termed Milankovitch cycles, which are also believed to have contributed to a variation in the global mean temperature by 5°C during the glacial and interglacial periods (Rehman et al., 2015). Although, such cycles take centuries to cause noticeable variations in the global mean temperature. Solar irradiance is mainly governed by three important factors: eccentricity in the Earth' orbit, the tilt and position of the Earth's axis, and the wobbling of Earth's axis of rotation, which are responsible for variations in the timing of perihelion. However, such changes are generally insignificant and do not contribute much to the global mean temperature in the long term (U.S. EPA, 2016). It is estimated that about 0.12 W m^{-2} has been contributed to global atmospheric radiative forcing due to the increment in solar irradiance since 1750 (Forster et al., 2007; Rehman et al., 2015), while the approximately 2.64 W m^{-2} increase in radiative forcing is due to anthropogenic activities (Rehman et al., 2015).

9.2.1.2 Volcanoes

Volcanic activity represents a natural process contributing to the cause of global warming through the emission of different tracer constituents directly into the atmosphere leading to alterations in atmospheric chemical composition. Although volcanoes are found in specific regions across the

globe, their effects can be spread widely across great distances through gases, dust, and ash that easily make their way into the atmosphere. Owing to atmospheric circulation patterns, eruptions at mid-latitude or higher latitudes generally cause a huge impact on the whole hemisphere, while volcanisms in the tropics can have a much greater impact on the climatic system in both hemispheres. Dust particles and volcanic ash reduce the amount of solar radiation reaching the surface of the Earth, thus, causing reductions in temperature in the troposphere and changing atmospheric circulation patterns (Myhre et al., 2013). However, the extent to which this occurs is still unclear. Although, the effects of large-scale volcanisms may last for a few days or weeks, climate patterns get disturbed for years due to the substantial outpouring of harmful ash and gaseous substances. Emissions of sulfuric gases from volcanic eruptions get converted into sulfate enriched aerosol particles consisting of about 75% H_2SO_4, which can linger in the stratosphere for 3−4 years after a volcanic eruption. Such major eruptions disrupt the Earth's radiative balance as the materials that enter into the atmosphere have tremendous potential to absorb and scatter a major portion of Earth's solar radiation, which is well-known as "radiative forcing" and can have long lasting effects on the global climate (Stenchikov et al., 1998).

Volcanic activity also releases enormous amounts of various greenhouse gases (GHGs), such as CO_2 and water vapor. However, such eruption does not cause much change in the global atmospheric concentration of these gases. Although, there have been times in history when intense volcanic activities have significantly enhanced the atmospheric concentration of CO_2 and caused global warming.

9.2.2 Anthropogenic Drivers

9.2.2.1 Greenhouse Gas Emissions

Demographic growth has been the primary reason behind the aggravation of atmospheric concentrations of GHGs. Global average economic growth has outpaced the process of GHG-intensity enhancement. Human induced GHG emissions have enhanced from 27 to 49 $GtCO_2eq\ y^{-1}$ between 1970 and 2010 (IPCC, 2014). GHG emissions rose on an average of 1 GtCO2eq y − 1 between 2000 and 2010 as compared to 0.4 GtCO2eq y − 1 between 1970 and 2000, (IPCC, 2014).

In the industrial age, atmospheric CO_2 concentrations have displayed an exponential growth rate, with the major sources of such emissions being industrial processes and fossil fuel combustion, which are responsible

for increases of about 78% (2000–10) in total GHG emissions (IPCC, 2014). Over the past 40 years, CO_2 emission due to fossil fuel combustion has enhanced consistently and contributed to 69% of global GHG emissions in 2010. It was further increased by about 3% (2010–11) and by between 1% and 2% (2011–12). Other anthropogenic activities, such as agricultural practices, deforestation, and other alterations in land use patterns constitute the second-largest contributor to GHG emission in this industrial era.

Since 1970, CO_2, methane (CH_4), nitrous oxide (N_2O), and fluorinated gas emissions have increased by about 90%, 47%, 43%, and less than 3%, respectively. In 2010, CO_2 remained the main human induced GHG, contributing about 76% of the total anthropogenic emissions (IPCC, 2014). Although the past four decades have experienced an enhancement of GHG emissions in every region across the globe, the increment patterns in different regions continue to be nonuniform. GHG emission has displayed an increment of 330% in the Middle East Asia and of 70% in Africa. GHG emissions from international transportation have also been growing rapidly.

9.2.2.2 Other Anthropogenic Factors

Ozone

Ozone is found in both the troposphere and stratosphere and its formation and destruction are driven by anthropogenic and natural activities. Abundances of ozone vary spatially and temporally owing to its unstable nature and mechanisms of production, destruction, and transport processes controlling its abundances, which contribute to the complexity of ozone radiative forcing calculations. Destruction of stratospheric ozone through photochemical reactions occurs in the presence of halogen species, such as chlorine and bromine. Stratospheric ozone depletion, which mainly contributes to a net negative radiative forcing, is most notable in the Polar regions.

In the tropospheric region, ozone is known as surface or ground level ozone, which is generally produced photochemically due to the emission of methane, oxides of nitrogen (NOx), carbon monoxide (CO), and nonmethane volatile organic compounds (VOCs) both near and far downwind of these precursor sources, resulting in a contribution to worldwide radiative forcing due to ozone abundances (Dentener et al., 2005).

Tropospheric ozone (O_3) is the most important secondary air pollutant causing significant phytotoxicity in crops, thus, leading to global yield

losses (Wilkinson et al., 2012). Presently, O_3 concentrations already display deleterious impacts on crop yields (Wahid, 2006), which are predicted to rise further at a rate of 0.3 ppb per annum worldwide (Wilkinson et al., 2012). Asian countries, such as India and China, are the most affected by increasing O_3 pollution owing to rapid economic growth, industrialization, and unfavorable meteorological conditions, which lead to high emissions of O_3 precursors (Zhang and Oanh, 2002).

Aerosol

Increased aerosol particles in the atmosphere due to anthropogenic activities have influenced global radiative forcing in mainly three ways: (1) through radiation–aerosol interactions, which is known as a direct effect, mainly involving the scattering and absorption of shortwave and longwave radiation; (2) through cloud–aerosol interactions, known as an indirect effect, resulting from alterations in the size and number of cloud droplets due to changes in aerosol; (3) through albedo pattern alteration as a result of absorbing-aerosol deposition onto snow and ice (IPCC, 2014). However, not all aerosols produce a negative radiative forcing. Aerosols, such as black carbon, absorb solar radiation and are responsible for producing a positive radiative forcing, leading to the warming of the atmosphere.

Land Use Changes

Alterations in land use patterns due to anthropogenic activities in the industrial era have also altered the albedo properties of land surfaces, primarily through afforestation and deforestation. There are strong scientific evidences that such changes have caused an increment in global surface albedo, resulting in a net negative (cooling) radiative forcing of about $-0.15\ \mathrm{W\ m^{-2}}$ (IPCC, 2014). However, such changes in land use patterns have also lowered surface albedo causing a net positive radiative forcing due to afforestation and pasture abandonment. In addition to direct radiative forcing, such activities have led to indirect forcing effects on the global climatic system, viz., changes in carbon cycles and alterations in the emission of dust particles through effects on the hydrologic cycle. Areas with significant irrigation generally govern surface temperatures and precipitation patterns through changes in the partitioning of energy from sensible to latent heating. Irrigation induced direct radiative forcing can be both negative and positive, depending on the balance of surface cooling and increased cloudiness effects (Cook et al., 2015).

Contrails

Contrails are visible evidence of humans' contribution to climate change. It is a special type of cloud/cirrus cloud that is produced due to the movement of a jet-engine aircraft in the mid to upper troposphere in the presence of high humidity. Contrails can be persistent in nature and can last for many hours, spreading and drifting with the local direction of the winds. During their movement, they lose their linear features and create additional cirrus cloudiness that interact with solar and thermal radiation to contribute to a global net positive radiative forcing and are, thus, harmful to the global climate system.

9.3 IMPACTS OF CLIMATE CHANGE ON CROP PLANTS

The climate changes over the past few decades have been quite rapid in various agricultural regions throughout the world, and increases in the levels of atmospheric CO_2 and O_3 have also been ubiquitous. The accelerating increase in atmospheric CO_2 as well as other GHGs has been well documented to occur since the industrial revolution. The inference is that the natural and life sustaining greenhouse effect is heightened, the Earth is warmed up, and the result is in the form of climate change. The virtual certainty that the phenomenon of climate change will continue in the future gives rise to numerous questions related to food security (Fig. 9.2).

Climate change can alter the productivity of plants either by influencing variables that directly affect plant growth, that is, temperature and

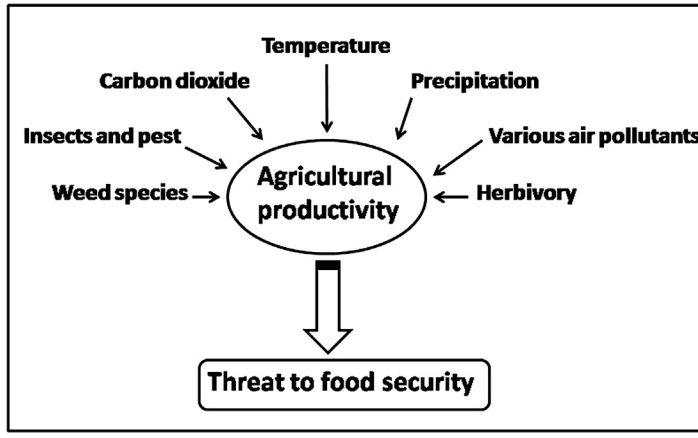

Figure 9.2 Various consequences of climate change affecting crop productivity.

precipitation, or indirectly by affecting equally crucial factors arising from altered agroecosystem conditions, such as soil properties, pests, weeds, and insects. Important consequences of climate change that affect crop productivity include:

- average mean temperature increase,
- alteration of precipitation patterns,
- various air pollutants,
- rising atmospheric CO_2 concentrations,
- change in sea level,
- herbivory,
- weed species, and
- insects and pests.

9.3.1 Average Temperature Increase

It is estimated that the average global temperature will increase by between 1.4°C and 5°C by the year 2100 (IPCC, 2014), while Rao et al. (2006) estimated an approximately 17% decrease in crop yields for every 1°C increase during the average growing season. Plants have learnt to adapt to fluctuations in temperature through the development of different stress tolerance strategies during the course of their evolution.

Heat stress affects the growth and morphology of various plants negatively Table. 9.1. Though, plant responses toward heat stress are dependent on many factors, such as plant species, age, and growth stage of plant. The responses of plant species also depend on the extent and length of the stress. Elevated temperatures expedite different aspects of plant metabolism (Pastore et al., 2017) and can affect crop yields by causing rapid crop development (Badeck et al., 2004). Due to rapid crop development, the duration of various aspects of plant metabolism are shorter (Larcher, 2003). Changes in the timing and duration of different plant developmental processes result in lower crop plant yields (Allen et al., 2018).

Temperature is a key factor in seed germination due to its affecting the rate of absorption of water and other substrates, which are crucial for the proper growth and development of seeds. Heat stress hinders seed germination and plant emergence and promotes poor seedling vigor, abnormal seedlings, reduced radicle and plumule growth, and causes an overall reduction in plant growth and development, modifications in photosynthesis, dry matter partitioning, and a decline in net assimilation rate (Kumar et al., 2011). High temperature for long durations, particularly

Table 9.1 Effects of various stress factors on wheat, rice, maize and soybean crops

Stress	Crops	Treatment	Effects	References
Temperature	Wheat	30°C/25°C (day/night)	Reductions in leaf size, grain size, yield, number of grains per spike, shortened period for booting, heading, anthesis, and maturity	Rahman et al. (2009)
	Rice	32°C (night temperature)	Reductions in yield, grain size, width and weight, and increased spikelet sterility	Mohammed and Tarpley (2010)
	Maize	35°C/27°C (day/night), 14 days	Reduced ear expansion and cob size by impairing hemicelluloses and cellulose synthesis due to a reduced photosynthate supply	Suwa et al. (2010)
	Soybean	38°C/28°C (day/night), 14 days	Decrease in photosynthetic rate and stomatal conductance, increased thicknesses of the palisade layers, membrane damage in chloroplast, thylakoid, mitochondria, and damage to cristae and matrix	Djanaguiraman et al. (2011)
Flooding	Wheat	Water logged pots (for 28 days)	Retarded root growth, reduction in biomass, low tiller number, shorter leaves and accelerated senescence, and decreased leaf nitrogen content	Malik et al. (2002)
	Rice	Stagnant flooding (50 cm above soil surface)	Reduction in number of tillers and panicles; significant decline in yield and harvest index; increased aerenchyma gas space, and declined root oxidase activity	Kuanar et al. (2017)
	Maize	Water logged (2 cm above soil surface)	Reduced biomass, lowered shoot growth, increased adventitious roots, and aerenchyma formed in roots	Abiko et al. (2012)
	Soybean	–	Various physical injuries, anaerobic stress conditions, poor vegetative growth, reduced photosynthetic activities, reduced nodulation, and significant yield losses	Tewari and Arora (2016)
Drought	Wheat	90%, 60%, and 30% of field capacity	Decreased biomass, leaf relative water content, chlorophyll, carotenoids, biomass, inorganic solutes (Ca, K, Mg), and increased organic solutes (soluble sugars and proline)	Loutfy et al. (2012)
	Rice	Mild (aerobic soil near field capacity) to severe	Significant decline in yield along with spikelet fertility, reduced plant height and number of tillers	Lafitte et al. (2006)
	Maize	Moderate to severe (100 and 150 mm evaporation from class A pan)	Reduced test weight, harvest index, yield, and biomass	Khalili et al. (2013)
	Soybean	30% of field capacity	Decreased photosynthetic rates, leaf water potentials, flowers, pods, leaf sucrose, and starch content	Liu and Stützel (2004)

(*Continued*)

Table 9.1 (Continued)

Stress	Crops	Treatment	Effects	References
Ozone	Wheat	Ambient + 10 ppb and ambient + 20 ppb	Damage to vegetative parts (shoot and root height, leaf number, leaf area), reproductive parts (pollen viability and viable pollen floret), and reduced yield	Sarkar and Agrawal (2010)
	Rice	Ambient + 10 ppb and ambient + 20 ppb	Induction of superoxide dismutase, catalase, peroxidase, ascorbate peroxidase, glutathione reductase, ascorbic acid, thiols, and phenolics. Reductions in RuBisCO, yield, and changes in the quality of grains	Sarkar et al. (2015)
	Maize	Ambient + 15 ppb and ambient + 30 ppb	Induction of ROS (superoxide radical and hydrogen peroxide), secondary metabolites (total phenol, flavonoids, and anthocyanin), antioxidative enzymes (superoxide dismutase, catalase, peroxidase, ascorbate peroxidase, and guaiacol peroxidase). Reduced yield	Singh et al. (2014)
	Soybean	82.5 and 61.3 ppb	Significant reduction in yield, leaf area index, chlorophyll content, increased antioxidative defense and phenolic content	Betzelberger et al. (2010)
Sulfur dioxide	Wheat	0.06 ppm	Significantly reduced plant height, leaf area, relative growth rate, biomass, and yield	Deepak and Agrawal (2001)
	Rice	0.001–0.008 ppm	Reduced plant height, number of tillers and leaves, leaf area, chlorophyll content, biomass, and yield	Singh et al. (2009)
	Maize	45, 70, and 110 nL SO_2 L^{-1}	Decrease in leaf soluble protein, aspartic acid, glycine, glutamine, and arginine concentration, while glutamic acid, asparagine, and alanine concentrations were increased	Ranieri et al. (1990)
	Soybean	1.2, 97, and 490 ppb	Reduced biomass, stunted plant growth, and lower grain yields	Li et al. (2011)
Carbon dioxide	Wheat	700 ppm	Increased plant height, leaf area, number of leaves and tillers, total biomass, harvest index, test weight, total soluble sugars, and starch content in seeds, while protein and total free amino acids were decreased	Mishra et al. (2013)
	Rice	Ambient + 200 μmol mol^{-1}	Declined content of protein, minerals (iron, zinc), vitamins (B1, B2, B5, and B9), and increase in vitamin E	Zhu et al. (2018)
	Maize	550 ppm	Increased grain yield and harvest index, cob length, cob diameter, grain weight cob^{-1}, number of grains cob^{-1}, and test weight. Decreased N and P concentrations in grain but increased K content	Abebe et al. (2016)
	Soybean	580 ppm	Increased seed yield, nodes, and number of branches, leaf area, chlorophyll, and leaf N content	Jin et al. (2017)

during reproductive periods, not only reduces total biomass, but also the reproductive efforts of crops (Polowick and Sawhney, 1988) mostly during flowering and fertilization (Morison and Lawlor, 1999), which can cause sterility, reduced pollen germination and viability, fruit abortion, and can finally result in complete crop failure (Teixeira et al., 2013). Incidences of agricultural disease are often linked with an increase in temperature (Ziska and Bunce, 2007).

Heat stress negatively affects various physiological processes in plants, such as reduced photosystem II (PSII) activity, photosynthetic pigments, enhanced reactive oxygen species (ROS) production, altered starch and sucrose synthesis, reduced ADP-glucose pyrophosphorylase, and invertase activities (Rodríguez et al., 2005). An exponential rise in air saturation vapor pressure because of increased air temperature leads to increased vapor pressure deficit between air and plant leaves which reduces water-use efficiency and ultimately plants lose more water per unit carbon gained (Ahad and Reshi, 2015). Physiological changes in plants are due to biochemical alterations in response to environmental stress. The plasma membrane acts as a primary target to heat stress by increasing the fluidity of lipid membranes responsible for changes in calcium influx along with cytoskeletal rearrangement, finally leading to the upregulation of mitogen-activated protein kinase and calcium-dependent protein kinase. These proteins, in turn, mediate the activation of various tolerance responses, including the production of antioxidant enzymes in defense against ROS or the production of osmolytes (Hasanuzzaman et al., 2013). Heat acclimation triggers the accumulation of heat shock proteins (HSPs) (Hua, 2009; Bray, 2000), and the activation of phytohormones, such as Abscisic acid (ABA) and other protective molecules, such as proline, sugars, sugar alcohols, tertiary sulfonium compounds, and tertiary and quaternary ammonium (Hasanuzzaman et al., 2013).

9.3.2 Alteration of Precipitation Pattern

Different studies have reported that GHG-induced atmospheric warming may lead to enhanced surface aridity and more drought events in the present century due to reductions in precipitation in tropical and subtropical regions (Dai et al., 2018), whereas the rising of extreme and sudden rainfall events are more likely to affect the rainfed low-lying areas of Asian countries, such as India, China, Bangladesh, and Nepal (Ismail et al., 2013). Different climate models have projected enormous increases in

precipitation intensity with reductions in frequency (Dai et al., 2018), which could potentially result in more dry periods and flooding events. As per available reports, about 10% of global agricultural areas are affected by flooding events and crop yield losses range between 15% and 80%, depending on other factors, such as species, duration of stress exposure, and different soil types (Patel et al., 2014).

9.3.2.1 Flooding Stress

Soil water logging generally induces hypoxia in the organs and plant parts that are submerged fully or partially, causing deleterious effects to the productivity of different crop plants, such as soybean (Tewari and Arora, 2016), rice (Kuanar et al., 2017), maize (Abiko et al., 2012), and wheat (Malik et al., 2002) (Table 9.1). Flooding stress caused a disruption in physiological mechanisms of the plants leading to yield losses and a reduction in productivity in different crop species. It is evident that flooding induced a reduction in stomatal conductance and assimilation rate and enhanced transpirational processes, conditional to the species-specific tolerance capacity to water logging stress (Promkhambut et al., 2010). Promkhambut et al. (2010) also reported that an increase in intercellular CO_2 in flooded plants caused a detrimental impact on the assimilation process in sweet sorghum cultivars as a consequence of ineffective diffusion of internal CO_2 from substomatal cavities to the specific site of carboxylation. Hypoxia is a common consequence of flooding stress which generally induces root and shoot injuries and disrupts the nutrient allocation mechanism of plants (Tewari and Arora, 2016).

Several adaptive mechanisms developed under flooding stress are:

1. As an effective strategy to develop proper anchorage and transportation of water and nutrients to different aboveground plant parts, plants produce adventitious roots under flooding stress (Promkhambut et al., 2010; Zaidi et al., 2003).
2. To maintain proper oxygen balance under stressful conditions, the development of lysigenous aerenchyma in the rooting system is a common adaptive mechanism of plants which reduces the number of oxygen consuming cells (Sauter, 2013). Such aerenchymal spaces also help in rapid oxygen diffusion over long distances within plants (Kuanar et al., 2017) and are essential for survival under hypoxic or anoxic conditions.
3. Under flooding conditions, the development of a barrier to manage radial oxygen loss in the outermost cellular layer of the roots has been

reported in maize species (*Zea nicaraguensis*) to prevent the diffusion of oxygen from the tip of the roots to the circumforaneous rhizospheric zone (Abiko et al., 2012).

4. Stomatal closure generally corresponds to an adaptive reaction of plants under flooding stress, inducing a reduction of root water permeability and a restriction in water loss through transpiration, thereby helping the plants survive under such conditions (Soldatini et al., 1990).

Different literatures have reported an enhancement in the level of antioxidants (ascorbic acid and glutathione) and antioxidative enzymes, such as ascorbate peroxidase (APX), superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and glutathione reductase (GR) to cope with the oxidative stress generated due to flooding stress (Hossain et al., 2009; Yan et al., 1996). It is evident that abiotic stress can cause a substantial increase in the total endogenous antioxidative enzyme concentration under flooding conditions, which further accelerates photooxidative injury due to an oxygen deficiency (Yordanova et al., 2004). Furthermore, Kuanar et al. (2017) has reported a declination in root oxidase activity at a faster rate under stagnant soil flooding conditions in rice plants, signifying a reduction in the oxygen releasing efficacy of roots, further generating greater oxidative damage due to hypoxic condition.

9.3.2.2 Drought Stress

According to a report by the IPCC, the emission pattern of GHGs will increase global warming further and will likely enhance extreme climatic events in the future (IPCC, 2014). Drought is usually a recurring climatic event resulting from a natural reduction in the amount of precipitation over an extended period of time (Wilhite, 2000). The growing impacts of climate change on natural water resources has led to changes in the pattern of precipitation globally (Dai, 2013); and the intensification of agricultural activities is affecting the dynamics of soil moisture (Zhang et al., 2017), which has led to the enhanced frequency and harshness of droughts worldwide (Table 9.1). Stomatal closure and reduced carbon uptake are common strategies utilized by crop plants to overcome drought stress, however, they lead to a rise in canopy temperature by lowering the latent heat (Bernacchi et al., 2007) and they further increase heat-related impacts causing negative effects on crop production. Climate change models predict that increased emissions of GHGs will create significant disturbances to hydrological systems, influencing freshwater systems negatively (Strzepek and McCluskey, 2007) and making agriculture vulnerable.

In the early developmental growth stage of plants, water deficiency is a limiting factor particularly affecting the phases of cell division, differentiation, and cell elongation and lead to a reduction in cell turgor pressure and other physiological events (Taiz and Zeiger, 2010). Harb et al. (2010), suggested acclamatory responses through cell wall expansion in *Arabidopsis thaliana* as an early avoidance strategy under water limiting conditions. Liu and Stützel (2004) reported a decrease in specific leaf area in drought treated plants determining a reduction in cell expansion and hence resulting in thinner leaves. Nonami (1998) suggested that cell elongation is primarily correlated with the water absorption capacity of the elongating cells under water deficient conditions.

Crop yield and productivity are basically determined by the allocation of biomass to the reproductive sink. A common observation reported from drought studies is that under water deficient conditions there is an enhancement of root-shoot biomass ratio, with a greater reduction in the shoot biomass as compared to root biomass (Erice et al., 2010). Water deficient conditions cause the accumulation of solutes in the root tips resulting in potential differences between the surrounding soil and the root hairs, which in turn attracts water to these tip and consequently plants are able to maintain root turgor pressure and growth (Liu and Stützel, 2004). A reduction in leaf biomass was also observed in *Jatropa curcas* L. seedlings by 28% of the total produced leaf biomass under drought stress (Achten et al., 2010).

The growth and development of several crops are affected under drought conditions, such as rice (Lafitte et al. 2006; Manickavelu et al., 2006), maize (Monneveux et al., 2006), soybean (Samarah et al., 2006), barley (Samarah, 2005), cow pea (Turk et al. 1980), *Amaranthus* spp. (Liu and Stützel, 2004), and wheat (Loutfy et al., 2012).

Furthermore, the impacts of drought lead to an alter physiology of plants. Cell contraction is resulted due to reduction of cellular volume which in turn induce enhancement of cell viscosity (Farooq et al., 2009). Such an increase in cell viscosity due to high concentrations of solute accumulation may prove to be detrimental for normal plant functioning and photosynthetic machineries (Hoekstra et al., 2001). Stomatal limitation has been documented under drought stress in different crop species, such as maize (Cochard, 2002), wheat (Khan and Soja, 2003), soybean (Ohashi et al., 2006), kidney bean (Miyashita et al., 2005), and rice (Praba et al., 2009). Besides stomatal closure, a reduction of stomatal size was also

reported under moderate drought conditions (Farooq et al., 2012). Klamkowski and Treder (2008) reported the CO_2 deficiency and stomatal closure contributed to a reduction in photosynthesis in strawberry cultivars under moderate drought conditions. Miyashita et al. (2005) also observed reductions in the photosynthesis and transpiration rates of *Phaseolus vulgaris* L. due to stomatal limitation.

Besides a reduction in stomatal conductance, nonstomatal limitations are also taken into account as a major factor in determining the detrimental impacts on carbon assimilation processes in plants under drought stress. Flexas and Medrano (2002) reported the downregulation of different metabolic activities due stomatal limitation under water stress conditions, which impaired ribulose-bisphosphate (RuBP) regeneration and adenosine triphosphate (ATP) synthesis ultimately inducing events of photoinhibition and the disruption of normal photochemistry. Drought induced increases in photorespiration in plants has been reported by Massacci et al. (2008), which could be an acclimation strategy to counter balance the over excitation in the PSII. Drought induced photorespiration, can also offset carbon fixation and assimilation processes leading to the generation of ROS in the photosynthetic tissues of plants (Farooq et al., 2012).

Plants often encounter ROS toxicity owing to a reduction in CO_2/O_2 ratio in photosynthetic tissues and the enhancement of photorespiration under water deficit conditions. Uncontrolled generation of ROS may result in membrane leakiness and lipid peroxidation, ultimately leading to malondialdehyde (MDA) production as well as the impairment of functional macromolecules, such as DNA, proteins, lipids, nucleic acid, and chlorophyll pigments (Moussa and Abdel-Aziz, 2008). Drought induced free radical bursts inside the cellular and subcellular components of plants induce the production of enzymatic antioxidants, such as SOD, CAT, GR, APX, POD, dehydroascorbate reductase (DHAR); and nonenzymatic antioxidants, like ascorbic acid, flavanoids, anthocyanins, carotenoids, and α-tocopherol, thereby imparting resistance against abiotic stress at different growth stages of plants (Reddy et al., 2004).

Accumulation of proline is one of the most important adaptive responses to drought stress in plants. Bandurska et al. (2017) reported an increase in proline concentration in the leaves and roots of barley. The accumulation of osmolytes, like amino acid, protein, and sugar is a common phenomenon directly correlated to the improvement of drought tolerance mechanisms owing to their capacity to cope with osmotic stress

and their role in the maintenance of nutrient homeostasis (Iqbal et al., 2014). An increased accumulation have been observed for free proline content accompanied by other free amino acids and soluble protein under preflowering drought stage in the leaves of peanut cultivars (Zhang et al., 2017), contributing to osmotic regulation and improving drought tolerance mechanism in the cultivars. Similarly, the enhancement of glycine betaine and free proline in maize plants highlights the protective role of these nonenzymatic antioxidant molecules against oxidative injury under drought stress (Moussa and Abdel-Aziz, 2008).

Drought has been a serious concern for agricultural crop yield losses, such as wheat (Zhao et al., 2017) maize, (Kamara et al., 2003), barley (Samarah, 2005), rice (Lafitte et al., 2006; Pantuwan et al., 2002), and chickpea (Mafakheri et al., 2010). Also the impact of drought on crop plants depends on the severity, which is directly correlated with the stringency and duration of the stress period. In barley, at post-anthesis, drought has been proven to be detrimental to grain yield irrespective of stress severity as reported by Samarah (2005). The study also documented a shortening of the duration of grain filling processes in barley under drought stress as compared to well-watered plants. Moreover, drought induced maturity acceleration associated with a faster rate of grain filling has been reported in common beans (*P. vulgaris* L.), which displayed a positive correlation to seed yield, determining the drought adaptation strategy in resistant cultivars (Rosales-Serna et al., 2004).

Various Air Pollutants

Ozone Pollution Ozone is a phytotoxic gas not emitted directly into the atmosphere; the formation of tropospheric O_3 in the atmosphere includes several photochemical reactions between primary air pollutants. Therefore, it is a secondary pollutant formed in the atmosphere through solar radiation-driven chemical reactions between O_3 precursor gases, for instance, CO, NOx, CH_4, and non-methane VOCs (Von Schneidemesser et al., 2015).

Ozone has toxic effects on vegetation (Ainsworth et al., 2012); it enters via the stomata and forms ROS. Although plants have the capacity to detoxify O_3 and ROS increased damage have been observed when the detoxification capacity reduced and finally leading to O_3 induced symptoms on the leaves (Burkey et al., 2007).

The impact of O_3 on plants, however, varies between crops, cultivars, agricultural practices, and environmental factors (Table 9.1). There are

various approaches to study the effects of O_3 on plants, such as exposure-response studies using open-top chambers, free air concentration enrichment (FACE) studies, and the biomonitoring of sensitive plants.

Symptoms of O_3 toxicity usually occur between the veins on the adaxial portion of the older and middle-aged leaves, but may also involve both abaxial and adaxial leaf surfaces for some species (Cho et al., 2011). O_3 induced visible foliar injuries, such as chlorotic stippling or interveinal yellowing, have been reported by Sarkar and Agrawal (2010) in the leaves of mature rice plants, under both ambient and elevated O_3 concentrations in open-top chambers (OTCs), and it was observed that the magnitude of the injury depends on the cumulative effect of both duration and concentration of O_3 exposure. Ahmad et al. (2013) observed the development of O_3 induced visible foliar injuries on onion, potato, and cotton plants when mean monthly O_3 concentrations exceeded 45 ppb in north-west Pakistan. Differential magnitudes of symptoms of ozone induced injury were also recorded for the different cultivars of clover (Chaudhary and Agrawal, 2013).

Responses to increased O_3 concentrations have been well pronounced on the growth and biomass of plants from several studies reported to date and such responses exhibited variability owing to species or cultivar differences and the different developmental stages of plants (Guidi et al., 2009; Morgan et al., 2003). Sarkar and Agrawal (2010) reported adverse impacts of ambient and elevated O_3 (ambient + 10 ppb and ambient + 20 ppb) doses on two wheat cultivars (HUW 510 and Sonalika) and observed that cultivar HUW 510 displayed a higher degree of O_3 damage in its vegetative parts than cultivar Sonalika, whereas damage to reproductive structures (viable pollen floret per plant and pollen viability) was greater in Sonalika as compared to HUW 510. Likewise, this variability in responses was used to discriminate O_3 sensitivity in 10 different wheat cultivars exposed to eight O_3 regimes by Saitanis et al. (2014). O_3 induced reductions in plant height, number of tillers, number of leaves, and total leaf area have been reported in different crop species, like wheat (Pleijel et al., 2018), maize (Singh et al., 2014), mung bean (Chaudhary and Agrawal, 2015), and soybeans (Singh et al., 2010).

O_3 induced biomass reduction in belowground plant parts is generally associated with the reduction in root:shoot ratio (Andersen, 2003). Furthermore, some studies have reported an increased carbon allocation in leaves due to O_3 exposure mainly attributed to a reduction in phloem loading and transportation to meet the higher carbon demand to repair

the O_3 induced foliar tissue damage (Cho et al., 2011). A meta-analysis study performed by Morgan et al. (2003) toward investigating the response of soybean (*Glycine max* (L.) Merr.) to an O_3 exposure of 60 ppb exhibited an approximately 21% reduction in shoot and root dry biomass. Moreover, Saitanis et al. (2014) also observed a reduction in total biomass in different wheat cultivars due to O_3 fumigation with a maximum reduction of about 24.9% in cultivar Akbar followed by 20.2% in cultivar Sufi. Meta-analysis data revealed that an increase in relative grain yield losses is associated linearly with O_3 concentration, showing maximum losses within a 20%–30% range for various sites in India, China, and the United States (Pleijel et al., 2018).

Several controlled environment and field studies have observed that current background O_3 concentrations are adversely affecting the yields of different crops species, such as wheat (Mishra et al., 2013; Sarkar and Agrawal, 2010; Rai et al., 2007), rice (Sarkar et al., 2015), soybean (McGrath et al., 2015; Singh et al., 2010, Jaoudé et al., 2008), maize (Singh et al., 2014), barley (Wahid, 2006), mustard (Singh et al., 2009), and mung bean (Chaudhary et al., 2013). A regression analysis study carried out by McGrath et al. (2015) showed that ambient O_3 concentrations in the United States resulted in approximately 5% and 10% yield losses in soybean and maize respectively during the period of 1980–2011 in rainfed field conditions. Feng and Kobayashi (2009) reported yield losses of more than 10% for wheat, soybean, and rice; and more than 20% for beans under projected O_3 concentrations of 51–75 ppb, thereby indicating that future increasing O_3 concentrations pose a serious threat to global food security. Furthermore, previous studies have observed higher O_3 sensitivity in leguminous crops followed by crops of the Poaceae family, such as wheat, rice, and barley (Sarkar and Agrawal, 2010; Feng and Kobayashi, 2009).

Effects of ambient O_3 on wheat crops were investigated by comparing the yields of OTCs with ambient air to filtered air, depicting an average yield loss of 8.4% at 35.6 to 13.7 ppb, with reductions in starch (10.9%) and protein (6.2%), as revealed by 33 experiments (from 3 continents and 9 countries using 17 cultivars along with 1 set of 4 cultivars) (Mills et al., 2018).

Physiological damage can occur early and even at low O_3 concentrations prior to the appearance of visible injury. Different experimental studies have been conducted to evaluate the effects of ambient and elevated O_3 exposure on physiological processes that have exhibited detrimental impacts on the assimilation rate of plants.

Five modern wheat cultivars were exposed to elevated levels of O_3 in a fully open air field experiment and significant impacts of elevated O_3 concentrations were depicted, such as increased lipid oxidation, and faster declines in pigments and photosynthetic rates. A lowered carboxylation rate causes a reduction in photosynthetic activity and electron transport rate (Feng et al., 2016). Lowering of g_s, and a decline in net photosynthetic capacity and carboxylation efficiency are some common O_3 induced phytotoxic impacts on the physiological processes of plants (Rai et al., 2011; Cho et al., 2011; Morgan et al., 2003). The impaired activity of mesophyll cells and structural damage to the cellular membrane, as evidenced by enhanced intercellular CO_2 concentrations and lipid peroxidation, are associated with O_3 induced photosynthetic loss, as reported by Rai et al. (2011). An O_3 induced alteration in photosynthetic electron transport rate in plants via a decrease in the efficiency of excitation capture, indicate a lowering of F_v/F_m ratio (Guidi et al., 2001). Reduced F_v/F_m ratio indicates photoinhibition to the PSII complexes, causing increased sensitivity of plants to light exposure (Rai et al., 2011).

The impacts of O_3 on vegetation are best correlated with accumulative stomatal O_3 flux, calculated over a species-specific time period, using a threshold for the stomatal O_3 flux (Mills et al., 2011). Harmens et al. (2018) reported that wheat yield and 1000-grain weight declined linearly with increasing O_3 flux, therefore, wheat yield is determined by the accumulated O_3 stomatal flux above a threshold value, irrespective of O_3 concentration. Similar response was observed by Osborne et al. (2016) on soybean cultivars.

O_3 flux in the apoplastic region is determined by uptake largely via stomatal aperture present on leaf surfaces. Although the mechanism through which O_3 influences stomatal conductance is still not clear, researches have postulated the activation of O_3 induced abscisic acid signaling pathway and outbursts of ROS directly in guard cells (Kangasjärvi et al., 2005). Due to the short residence time of O_3 in the apoplastic region, it gets rapidly degraded to form ROS and/or reacts with cellular biomolecules, such as protein, lipid, DNA, or apoplastic fluid present there (Mishra et al., 2013). ROS induces cellular membrane damage and causes detrimental effects to the normal functioning of cells. Plants have developed various mechanisms to make use of nonenzymatic and enzymatic antioxidants present in different cellular compartments to cope with oxidative injury caused by O_3 stress (Singh et al., 2015).

Elevated CO_2 Concentration Atmospheric concentrations of CO_2 have increased from 280 ppm, at the beginning of the industrial revolution to 411 ppm currently and are expected to rise to 750 ppm by 2100 (IPCC, 2014). This trend of unprecedented increasing CO_2 concentrations is of concern to agricultural production and food quality because elevated atmospheric carbon dioxide levels have revealed strong diversified effects on crops (Table 9.1). Although the effects depend on plant species and nutrient availability (Zhang et al., 2017) as well as on the specific processes that plants use to fix carbon during the process of photosynthesis (Wang et al., 2008), it is well accepted that elevated atmospheric CO_2 markedly affects numerous plant processes, like growth (O'leary et al., 2015), biomass allocation (Wang and Taub, 2010), biochemical processes (Arndal et al., 2014), photosynthesis (Kimball, 2016), and respiration (Xu et al., 2015). Some of the most common responses of crop plants toward elevated CO_2 concentrations include growth rate changes (Xu et al., 2014), biomass allocation (White et al., 2012), rate of nutrient uptake (Prior et al., 2008), and water-use efficiency (Varga et al., 2015).

Plants have been categorized primarily into three categories (C_3, C_4, and CAM plants) depending on their operational photosynthetic pathway and variations in the physiological response of plants to carbon dioxide enrichment, mainly CO_2 fixing enzymes. C_3 plant species, such as wheat, rice, oilseeds, and pulses respond favorably to elevated CO_2 when compared to C_4 and CAM species, as C_3 plants are competitively inhibited by O_2. C_4 plants, such as sorghum, maize, and sugarcane display little or no photosynthetic response to elevated CO_2 because the C_4 pathway is completely CO_2 saturated (Cousins et al., 2003). An increase in atmospheric CO_2 usually increases plant development and growth by improving photosynthesis and water-use efficiency. Increasing atmospheric CO_2 might be beneficial for crops, particularly C_3 plants. However, the advantages may or may not be realized in long-term growth due to interactions of various environmental factors (Poorter et al., 2013). Fernando et al. (2015) and Broberg et al. (2017) observed declines in several nutrients along with protein concentrations in food crops, while Högy and Fangmeier (2008) and Myers et al. (2014) showed decreases in vitamins, some macro and micro elements of food crops, under elevated CO_2.

It has been well identified that elevated CO_2 accelerates photosynthesis but the degree of stimulation depends on the nature of the species as well as on environmental conditions. Experiments carried out under ideal conditions reflected that doubling the CO_2 concentration increased

photosynthesis by 25%–45% (Ainsworth and Long, 2005) and yield by 10%–20% in C_3 crops, while in C_4 crops under natural atmospheric conditions, doubling of CO_2 leads to increased photosynthesis by 10%–25% and yield by 0%–10% (Ainsworth and Long, 2005). Sage et al. (1989), and Chen et al. (2005) reported the acclimation or downregulation of photosynthesis, that is, after long-term exposure to elevated CO_2 the effect on photosynthetic rates were either positive or negative and were variable among and within species. Decreased leaf nitrogen and disturbed source-sink balance due to an increase in sugar production may be probable reasons of photosynthetic acclimation (Seneweera et al., 2011). However, Radin et al. (1987) showed acclimation does not occur in *Gossypium hirsutum* grown at elevated CO_2 concentration.

High atmospheric CO_2 in general causes reductions in stomatal density (Teng et al., 2009), stomatal conductance (Gao et al., 2015), leaf transpiration (Katul et al., 2009), and evapotranspiration/water use (Bernacchi and VanLoocke, 2015). Contradictory responses are also reported as reverse responses might occur during interactions between CO_2 and other climatic factors. Elevated CO_2 cut down the amount of water required to produce an equivalent amount of biomass. This enhancement in water-use efficiency is due to a closing of the stomata to adjust to the CO_2 flux and these partially closed stomata monitor the amounts of H_2O that are transpired by the plant (Lambers et al., 1998).

The elevated CO_2 environment plays a significant role in various stages of growth, as well as economic yield of agricultural crops. Plant growth responses comprise of increases in leaf size (Ghannoum et al., 2000), specific leaf weight, leaf thickness, leaf area index, branches, nodes (Allen, 1990) stem length, and extensively long roots (Allen, 1990; Bowes, 1993; Lee-Ho et al., 2007). The effects of increased CO_2 also include changes in allocation of biomass to roots from leaves (Stulen and Den Hertog, 1993). Elevated CO_2 enhances the flower, fruit, and seed number (Jablonski et al., 2002), which results in higher total seed mass (Jablonski et al., 2002), while on the other hand, it reduces protein content in flowers and seeds (Ziska et al., 2004). Plant chemical composition is altered due to elevated CO_2 which affects growth (Poorter et al., 1997). CO_2 enhancement causes the accumulation of nonstructural carbohydrates along with soluble phenolic compounds, while declines have been reported for minerals, nitrogen, and phosphorus (Rogers et al., 1999). Plants under increased CO_2 have higher photosynthetic nitrogen use efficiency and higher nitrogen use efficiency (Tuba et al., 2003). Growth,

biomass, and yield for C_3 species are increased under CO_2 enriched environments (Deepak and Agrawal, 2001a,b). It was estimated that a doubling of CO_2 from 340 to 680 ppm would increase the growth and yield of major crops by 10%–50% (Warrick, 1988).

Atmospheric CO_2 enrichment, however, provides plants with counteracting tendencies against various environmental stress factors to avoid harmful effects on their growth and development. An increase in CO_2 ameliorates the effects of increasing temperatures (Idso and Idso, 1994), drought (Karl et al., 2009), O_3 pollution (Karl et al., 2009), herbivory, and pest stress (Bidart-Bouzat et al., 2005).

Sulfur Dioxide Sulfur dioxide (SO_2) is a gaseous pollutant present in the atmosphere, which is acidic in nature, with a pungent and irritating odor. SO_2 is released from volcanic eruptions, rock weathering processes, sea spray, microbial activities, and hot springs, while anthropogenic activities also generate SO_2 from the combustion of biomass and fossil fuels, vehicular exhaust emissions, and industrial processes have supplemented extra SO_2 emissions into the atmosphere. The atmospheric concentration of SO_2 increased to a severe level after the industrial revolution which was documented in London in 1952 as London smog which drew the attention of the scientific community of that time. Lu et al. (2011) reported that between 1996 and 2000, China displayed a relative reduction in SO_2 concentration of 13% as a consequence of the reduction in economic growth and the implications of air pollution control legislation. But such economic growth again took place dramatically during 2000–06 and decreased again between 2006 and 2010.

In nature, pollutants do not occur singly but in combination with other gaseous pollutants and their combined effects are much more damaging to plants. SO_2 pollution is not restricted only to urban areas or the site of emission, but also extends to rural areas where it induces phytotoxicity to vegetation and agriculture (Agrawal et al., 1987). The degree of phytotoxicity induced due to SO_2 pollution is impelled by the concentration of SO_2 (Table 9.1), present meteorological conditions, the duration of exposure, and also the genetic composition of the plants (DeKok, 1990). The entry of air pollutants is mainly driven through stomatal openings present on the leaf surface. Agrawal et al. (1987) reported that after entry through stomatal openings, SO_2 reacts with oxygen molecules (O_2) to produce sulfite and bisulfate ions, which further get photooxidized into sulfate ions, generating more free radicals concomitant with the formation

of superoxide radical ($\dot{O}^{-}_{2}$) which causes adverse impacts on the health of the plant.

Marginal and bifacial chlorosis, followed by necrosis, are some of the most common visible symptoms of SO_2 toxicity in plants. Upon entry through the stomatal opening, SO_2 reacts with water and the formation of acid takes place, leading to the development of injuries at the margins and degradation in leaf surface area, which in turn affect the assimilative efficacy of plants. Rai and Agrawal (2008) observed significant declines in the photosynthetic rate and stomatal conductance of rice when the plants were exposed to ambient SO_2 concentration. Various studies have displayed that SO_2 toxicity may cause chlorophyll pheophytinization and swelling of thylakoids under SO_2 exposure (Wellburn et al., 1972). Agrawal et al. (1987) suggested that the detoxification of free radicals takes place upon exposure to high SO_2 concentrations in tolerant cultivar/species.

Oxides of Nitrogen Oxides of nitrogen have adversely affected forest ecosystems, and it has been observed that humid temperate regions of the world are facing the threat of increased nitrogen deposition (Dise and Wright, 1995; Adams et al., 2004) leading to a situation popularly known as nitrogen saturation. Högberg et al. (2006) has reported that nitrogen saturation is caused due to an excess in the availability of ammonium and nitrate of the total combined plant and microbial nutritional demands.

Oxides of nitrogen play a significant role in the O_3 formation process. It is evident that biomass burning contributes to total NOx emissions (Sahai et al., 2011) maximally. Studies have reported that the combustion of agricultural residues from different staple crops, such as wheat, rice, and sugarcane have enhanced NOx emissions from 58.9 to 117.4 Gg from 1980 to 2010 (Oksanen et al., 2013).

The entry of NOx into plants is governed by the cuticular region and stomatal opening and once inside the mesophyll layer, NOx reacts with water resulting in the formation of chlorotic and necrotic patches on leaf surfaces. Coniferous trees are affected due to chronic nitrogen wet and dry deposition resulting in frost damage and disturbances in the normal physiological functioning of plants which in turn reduces their productivity. Redling et al. (2013) reported that human induced acidic precipitations are gradually altering the pH of soil, which further changes its cation exchange capacities, leading to the increased uptake of mobile metal by plants which ultimately cause disturbances to crop productivity.

According to Rai et al. (2007), wheat crop (*Triticum aestivum* L.) grown in nonfiltered chambers displayed phytotoxic effects of NOx pollution, which induced the production of secondary metabolites and hence crop yield was compromised.

Volatile Organic Compounds VOCs are organic compounds produced from anthropogenic emissions. They are also released naturally from plants, having sufficiently high vapor pressure to get vaporized into the atmosphere under normal conditions (Yuan et al., 2009). The most common VOCs are alkanes, carnonyls, alkenes, esters, alcohols, and acids (Peñuelas and Llusià, 2003). Laothawornkitkul et al. (2009) has estimated that total VOC emissions from vegetation are approximately $700-1000 \times 1012$ g C y^{-1} per annum globally and studies have projected that a rise of 2°C–3°C in the mean global temperature could further enhance such biogenic emissions by 30%–45%.

Anthropogenic sources of VOCs emissions mostly include the incomplete combustion of fuel, evaporation of fuel, biomass burning, and several industrial processes (Holopainen, 2004). Hallquist et al. (2009) estimated that VOCs emissions from biogenic sources have exceeded that of anthropogenic sources in the atmosphere. Plants have the potential to emit a considerable amount VOCs, such as isoprene and mono- and sesquiterpenes. Such VOCs take part in photochemical reactions to produce secondary phytotoxic pollutants, such as surface level ozone. Some common responses in plants to VOCs toxicity include chlorosis, plant biomass reduction, decreased number of flowering plants^{-1}, and reductions in leaf area (Cape, 2003).

Change in Sea Level Alterations in sea level will affect plant growth and productivity in some regions of the globe. Allison et al. (2009) reported that there has been a 12–22 cm rise in sea level globally during the 20th century, and new scientific observations confirm an increase of about 3.4 mm per annum in the past two decades. Such rises in sea level induce vulnerability in low-lying agricultural lands to inundation, which can result in the loss of agricultural land and poses a threat to crop production in these areas. Warming of air temperatures has led to an increase in sea level as a consequence of the melting of glaciers and polar ice as well as the thermal expansion of the sea, in the past part of the 20th century (Douglas, 1997), exposing arable land to wastewater contamination to a severe extent (ESCAP, 2009). All these factors are responsible for the reduction of crop production in the immediate future.

Weed Species The presence of weeds in crop fields can cause reductions in yield as a consequence of competition for moisture, light, space, and mineral nutrients (Xu et al., 2009). Temperature increases due to global climate change will positively affect the survival of weed species (Woodward and Williams, 1987) and consequently their growth and distribution. Mostly such weeds species avoid the higher latitudinal regions owing of the prevalence of low temperatures, making their survival almost impossible. Therefore, such species are restricted to tropical and subtropical regions (Holm et al., 1997). Rahman and Wardle (1990) reported that the warming of air temperatures will facilitate and stimulate the northward expansion of these weeds as climate change influences the distribution of such invasive species.

Several studies have reported that plant growth and development are generally affected by the interaction of various biotic and abiotic factors simultaneously. It is evident that the presence of weeds can amplify the deleterious impacts of air pollutants, such as O_3, and can cause an increased loss in crop productivity as compared to, for example, under O_3 stress alone (Li et al., 2016). Li et al. (2013) elucidated the performance of weed species and crop plants under O_3 stress and reported significant resistance in weed species owing to the presence of exceptionally developed antioxidant defense systems. Therefore, the invasion of weed species in crop fields concomitant with other abiotic and biotic factors may result in competition and the related potential damage to crops, and hence, the adaptation of weed management practices is essential to monitor such types of climate change induced crop yield losses (Ghosh et al., 2018).

Insects and Pests Generally, the warming of air temperatures promotes and accelerates the life cycle and growth of different insects and pests. GHG-induced global warming promotes successful colonization by insects and pests due to their early maturation and migration (Bale and Hayward, 2010). There will be an overall positive feedback on the amplification of different ranges of insects due to such temperature increases (Parmesan, 2006; Walther, 2010). Dixon (2012) has reported that about 20%–25% of harvested crops are lost to pre- and postharvest diseases worldwide and climatic change is expected to amplify such losses. Such a situation of the projected increase of extreme climate events will give rise to outbreaks of pest populations (Hawkins and Holyoak, 1998; Srygley et al., 2010), which will further hamper the growth, productivity, and yield of plants.

Presently, it has been depicted that crop plants are more at risk of getting infected by pests and insects. Climate change causes alteration of temperature scale, precipitation pattern, wind velocity, and periodicity. These changes further alter the vigor and activities of different types of pathogens. Some pathogens causing harm to crops and harvested products have evolved as more active and damaging owing to the expansion of their geographical ranges as a result of climate change (Dixon, 2012). The enrichment of atmospheric CO_2 levels can further increase the production of simple sugars in the leaves of plants and can in turn reduce the leaf nitrogen content. Such a situation can promote the consumption of more leaves by pest species in order to meet their metabolic requirements for nitrogen, inducing a more severe pest attack. Moreover, higher temperatures reduce the effectiveness of some pesticides and further favor the growth of many disease carrying pathogens.

9.4 CONCLUSION

Global climate change has become univocal, and the probable impacts of which are projected to aggravate further if the emission of GHGs persist in an unmitigated way. Since 1950, about 20% more carbon dioxide has been added into the Earth's atmosphere, increasing the chances of potentially disastrous outcomes. The consequences of global climate changes are difficult to predict owing to their complexity and the incomplete insight into several atmospheric processes and interactive relationships among different environmental variables, such as temperature, radiation, water availability, soil salinity, and soil nutrition. Presently, humanity has been challenged with improving agricultural productivity in order to feed the global population adequately and to achieve future sustainability under such disastrous consequences of global climate change. Hence, a cumulative effort is necessary to exploit various adaptive strategies and plausible mitigation measures including more research and the development activities using different crops/or cultivars to gain an enhanced understanding of ways to counteract such negative impacts of climate change.

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